TEN YEARS OF MISR OBSERVATIONS FROM TERRA: LOOKING BACK, AHEAD, AND IN BETWEEN

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1. INTRODUCTION

The Multi-angle Imaging SpectroRadiometer (MISR) instrument was launched into polar Earth orbit aboard NASA's Terra satellite on December 18, 1999. MISR contains 9 pushbroom cameras pointed at nadir and along-track view angles of 70.5º, 60º, 46.1º, 26.1º forward and backward of nadir, each with spectral bands at 446, 558, 672, and 866 nm. Surface and atmospheric targets within the observed swath (~400 km) are viewed at all 9 angles over a span of 7 minutes with an intrinsic spatial resolution of 275 m. No instrument that combines MISR's attributes—multiangle imaging at moderately high spatial resolution with near-simultaneous temporal sampling; stable and accurate on-board calibration suitable for climate-quality science; and global coverage—had flown in space prior to Terra launch, nor is there is a similar capability currently available on any other satellite platform. Examples of MISR applications to terrestrial climate and environmental studies are briefly presented below.

2. SCIENTIFIC APPLICATIONS

Clouds and climate: Cloud-top heights (CTH) are retrieved from MISR data using a stereo pattern-matching approach insensitive to atmospheric temperature profile, emissivity, and radiometric calibration drifts, thereby providing climate diagnostics independent of errors that adversely affect infrared techniques, e.g., in areas subject to temperature inversions [10], [12]. Instantaneous MISR CTH are accurate to about ±500 m. MISR CTH retrievals exhibit a tri-modal vertical distribution in the tropics, and show exceptionally high quality and sensitivity for detection and height determination of low-level clouds [27]. This is important because such clouds are major contributors to tropical cloud feedback uncertainties in climate simulations [1]. Averaging reduces the random component of uncertainties to precisions characteristic of the sampling error, estimated to be ±8 m for annual global means, providing a uniquely sensitive climate metric for detecting trends in cloud heights [4].

Height-resolved tropospheric winds: Using multi-camera stereo, MISR has for the first time enabled a pole-to-pole, height-resolved atmospheric wind measurement system [14], [28]. The global data product, which provides cloud-tracked atmospheric wind vectors at 70.4 x 70.4 km^2 horizontal and 500 m vertical resolution, is valuable for retrospective evaluation and improvement of weather and climate models. Validation against rawinsondes and radar wind profilers indicate uncertainties smaller than obtained from geostationary platforms and superior height assignments [3], [13], [20]. Spatially and temporally matched zonally averaged wind profiles vs. height show excellent agreement between MISR and numerical analysis models, with systematic differences showing up at mid-levels in the tropics [11]. Recent algorithm enhancements are being used to generate a high-resolution wind product over tropical hurricanes, with horizontal wind resolution in the cross-track direction of 1.1 km for use in cyclone inner-core dynamics and intensification process studies.

Aerosol sources, injection, and transport: MISR stereo imagery makes possible global measurement of the heights and advection speeds of smoke plumes, volcanic plumes, and dust clouds. Using fire detections from the Moderate Resolution Imaging Spectroradiometer (MODIS), a multi-year climatology of smoke injection heights from MISR [22] is providing new insights into how smoke injection depends on environmental variables [16], [25]. The public archive (http://www-misr2.jpl.nasa.gov/EPA-Plumes/) contains data for >7000 smoke plumes in North America, Siberia, and Africa. For about one-fifth of wildfires, smoke is injected into the free troposphere, where particles can remain for long periods and be transported great distances. The data also show that smoke tends to become trapped at levels of relative atmospheric stability, providing a useful parameterization for chemical transport models [15]. MISR also provides accurate aerosol optical depths (AOD) over land, including bright desert and urban source regions [21]. Koven and Fung [18] identified landscape characteristics common to dust-producing regions in the Sahara Desert, and the resulting models of dust spatial distributions agree well with MISR observations, representing an improvement over existing parameterizations. To aid estimates of transported dust mass flux, Kalashnikova and Kahn [17] showed how MISR combined with MODIS aerosol products characterize the evolution of Saharan dust plumes as they cross the Atlantic Ocean.

Particulate air pollution: Di Girolamo et al. [6] analyzed four years of MISR data and showed that a concentrated pool of wintertime particulate pollution over the state of Bihar, India is caused by a unique confluence of human activity, regional topography, and meteorology. These aerosols pose a significant health risk to some 100 million people. More recently, Dey and Di Girolamo [5] used nine years (2000-2008) of MISR retrievals of particle properties over the Indo-Gangetic Basin to attribute high aerosol optical depths (AOD) to anthropogenic emission sources, aided by subsiding air in the post-monsoon and winter seasons and transport of dust in the pre-monsoon and monsoon seasons. Using MISR discrimination of particle sphericity, Liu et al. [19] improved the relationship between total-column AOD and surface PM2.5 (fine particulate matter, a regulated air pollutant) in both the eastern and western US, with the largest improvement occurring in the west. This breakthrough is particularly significant in light of earlier studies that showed poor correlations with total column AOD and PM2.5 in the western US, and constitutes an important step toward a satellite-based monitoring system.

Surface structure: Bidirectional reflectance measurements of vegetation are governed in large measure by canopy structure [26], and a remarkable consequence is sensitivity of MISR data to canopy heights and aboveground biomass [2]. MISR observations of forward and backward scattered surface radiation, calibrated using airborne lidar, have been used to map roughness of the Greenland ice sheet (related to ice sheet melting and flow) with an accuracy of a few cm [23]. This work capitalizes on the unanticipated sensitivity of MISR to ice roughness, which was discovered in imagery over James Bay, Canada, acquired on the first orbit of data after opening of the instrument's cover [7]. Enhanced specular reflection over wet surfaces was used to detect extensive dewatering—a primary cause of building collapse after the January 2001 Gujarat (India) earthquake—far from the epicenter and in remote areas inaccessible to ground teams [24].

3. CONCLUDING REMARKS

Complementing the novel design of the MISR instrument, innovative data processing algorithms have been developed to mine the information content of angular reflectance anisotropies and to perform multi-camera stereophotogrammetry and time-lapse imagery, opening new avenues for inferring 3-D structure and dynamics of the atmosphere and surface [8]. The 10-year (and counting) MISR data record provides unprecedented opportunities for characterizing long-term trends and variability, as well as 3-D information about cloud, aerosol, and surface targets conventionally thought to be accessible only to active sensors. Technology development is underway to extend future multiangle measurements to broader spectral range (ultraviolet to thermal infrared), wider spatial swaths (enabling more rapid global coverage), and accurate polarimetric imaging [9]. Data processing approaches that take advantage of continually increasing computer speeds are also being explored to facilitate algorithm advances that were not operationally practical at the beginning of the Terra mission.

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4. REFERENCES

[1] Bony, S. and J-L. Dufresne (2005). Marine boundary layer clouds at the heart of tropical cloud feedback uncertainties in climate models. *Geophys. Res. Lett.* 32, L20806, doi:10.1029/2005GL023851.

[2] Chopping, M., A. Nolin, G.G. Moisen, J.V. Martonchik, and M. Bull (2009). Forest canopy height from the Multiangle Imaging SpectroRadiometer (MISR) assessed with high-resolution discrete return lidar. *Rem. Sens. Environ.* 113, 2172-2185.

[3] Davies, R., A. Horvath, C. Moroney, B. Zhang, and Y. Zhu (2007). Cloud motion vectors from MISR using sub-pixel enhancements. *Rem. Sens. Environ.* 107, 194-199.

[4] Davies, R. and M. Molloy (2008). Trends in equatorial cloud-top heights from MISR since 2000. AGU Fall Meeting, San Francisco, CA, abstract A41B-0098.

[5] Dey, S. and L. Di Girolamo (2009). Aerosol properties over the Indian Subcontinent using nine years (2000-2008) of Multiangle Imaging SpectroRadiometer observations: climatology and hot spots. AGU Fall Meeting, San Francisco, CA, abstract U33B-0058.

[6] Di Girolamo, L., T.C. Bond, D. Bramer, D.J. Diner, F. Fettinger, R.A. Kahn, J.V. Martonchik, M.V. Ramana, V. Ramanathan, and P.J. Rasch (2004). Analysis of Multi-angle Imaging SpectroRadiometer (MISR) aerosol optical depths over greater India during winter 2001-2004. *Geophys. Res. Lett.* 31, L23115, doi:10.1029/2004GL021273.

[7] Diner, D.J., Beckert, J.C., Bothwell, G.W. and Rodriguez, J.I. (2002). Performance of the MISR instrument during its first 20 months in Earth orbit. *IEEE Trans. Geosci. Rem.Sens.* 40, 1449-1466.

[8] Diner, D. J., B. H. Braswell, et al. (2005). The value of multiangle measurements for retrieving structurally and radiatively consistent properties of clouds, aerosols, and surfaces. *Rem. Sens. Environ.* 97, 495-518.

[9] Diner, D.J., A. Davis, B. Hancock, G. Gutt, R.A. Chipman, and B. Cairns (2007). Dual photoelastic modulator-based polarimetric imaging concept for aerosol remote sensing. *Appl. Opt.* 46, 8428-8445.

[10] Garay, M. J., S. P. de Szoeke, and C. M. Moroney (2008). Comparison of cloud-top heights retrieved from ISCCP, MODIS, and MISR with coincident ship-based measurements for the marine stratocumulus region off the western coast of South America. *J. Geophys. Res.* 113, Art. No. D18204.

[11] Garay, M.J., K.J. Mueller, C.M. Moroney, V. Jovanovic, D.L. Wu, and D.J. Diner (2009). 10 years of height resolved, cloud-track, vector winds from MISR. AGU Fall Meeting, San Francisco, CA, abstract U33A-0050.

[12] Harshvardhan, G. Zhao, L. Di Girolamo, and R.N. Green (2009). Satellite-observed location of stratocumulus cloud-top heights in the presence of strong inversions. *IEEE Trans. Geosci. Remote Sens.,* doi:10.1109/TGRS.2008.2005406.

[13] Hinkelman, L.M., R.T. Marchand, and T.P. Ackerman (2009). Evaluation of MISR cloud motion vectors using NOAA radar wind profiler data. *J. Geophys. Res.* 114, Art. No. D21207, doi:10.1029/2008JD011107.

[14] Horváth, Á., and R. Davies (2001). Simultaneous retrieval of cloud motion and height from polar-orbiter multiangle measurements. *Geophys. Res. Lett*. **28**, 2915-2918.

[15] Kahn, R. A., W.-H. Li, C. Moroney, D. J. Diner, J. V. Martonchik, and E. Fishbein (2007). Aerosol source plume physical characteristics from space-based multiangle imaging, *J. Geophys. Res.* 112, D11205, doi:10.1029/2006JD007647**.**

[16] Kahn, R. A., Y. Chen, D. L. Nelson, F.-Y. Leung, Q. Li, D. J. Diner, and J. A. Logan (2008). Wildfire smoke injections heights—two perspectives from space, *Geophys. Res. Lett*. 35, L04809, doi:10.1029/2007GL032165.

[17] Kalashnikova, O.V., and R.A. Kahn (2008). Mineral dust plume evolution over the Atlantic from MISR and MODIS aerosol retrievals. *J. Geophys. Res.* 113, D24204, doi:10.1029/2008JD010083..

[18] Koven, C.D., and I. Fung (2008). Identifying global dust source areas using high-resolution land surface form. *J. Geophys. Res.* 113, D22204, doi:10.1029/2008JD010195.

[19] Liu, Y., P. Koutrakis, and R. Kahn (2007). Estimating PM2.5 component concentrations and size distributions using satellite-retrieved fractional aerosol optical depth: Part 1 - Development of methods. *J. Air. Waste Mgmt. Assoc.* 57, 1351-1359.

[20] Marchand, R.T., T.P. Ackerman, and C. Moroney (2007). An assessment of Multiangle Imaging Spectroradiometer (MISR) stereo-derived cloud top heights and cloud top winds using ground-based radar, lidar, and microwave radiometers. *J. Geophys. Res.* 112, D06204, doi:10.1029/2006JD007091.

[21] Martonchik, J.V., D.J. Diner, R.A. Kahn, B.J. Gaitley, and B.N. Holben (2004). Comparison of MISR and AERONET aerosol optical depths over desert sites*,* *Geophys. Res. Lett.* 31, doi:10.1029/2004GL019807.

[22] Nelson, D.L., Y. Chen, R.A. Kahn, D.J. Diner, and D. Mazzoni (2008). Example applications of the MISR INteractive eXplorer (MINX) software tool to wildfire smoke plume analyses. *Proc. SPIE* 7089, 708909, doi:10.1117/12.795087.

[23] Nolin, A.W. and S. Coyote (2009). It's a rough place: Satellite mapping of the Greenland Ice Sheet from MISR. AGU Fall Meeting, San Francisco, CA, abstract U33A-0042.

[24] Pinty, B., N. Gobron, M.M. Verstraete, F. Mélin, J-L. Widlowski, Y. Govaerts, D.J. Diner, E. Fielding, D.L. Nelson, R. Madariaga, and M.P. Tuttle (2003). Observing earthquake-related dewatering using MISR/Terra satellite data*.* *EOS Trans. Amer. Geophys. Union* 84, 37-43.

[25] Val Martin, M., J.A. Logan, R. Kahn, F.-Y. Leung, D. Nelson, and D. Diner (2009). Smoke injection heights from fires in North America: analysis of 5 years of satellite observations. *Atmos. Chem. Phys. Discuss.* 9, 20515-20566.

[26] Widlowski, J.-L., B. Pinty, N. Gobron, M. M. Verstraete, D. J. Diner, and A. B. Davis (2004). Canopy structure parameters derived from multi-angular remote sensing data for terrestrial carbon studies. *Climatic Change*, 67, 403-415.

[27] Wu, D.L., S.A. Ackerman, R. Davies, D.J. Diner, M.J. Garay, B.H. Kahn, B.C. Maddux, C.M. Moroney, G.L. Stephens, J.P. Veefkind, and D.M. Vaughan (2009). Vertical distributions and relationships of cloud occurrence frequency as observed by MISR, AIRS, MODIS, OMI, CALIOP, and CloudSat. *Geophys. Res. Lett.* 36, L09821.

[28] Zong, J., R. Davies, J.P. Muller, and D.J. Diner (2002). Photogrammetric retrieval of cloud advection and top height from the multi-angle imaging spectroradiometer (MISR). *Photogramm. Eng. Rem. Sens.* 68, 821-830.